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A Theoretical Model of Phase Changes of a Klystron Due to Variation of Operating Parameters

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A mathematical model for phase changes of the VA-876 CW klystron amplifier output is presented and variations of several operating parameters are considered. The theoretical approach to the problem is based upon a "gridded-gap" modeling with inclusion of a second-order correction term so that actual gap geometry is reflected in the formulation. Physical measurements are contrasted to theoretical calculations.

I. Introduction

Phase stability of klystron amplifier output in the regime of 10^{-14} to 10^{-16} $\sigma\Delta f/f$ in one hour is currently a growing concern. Interest in the subject is sparked by recent proposals to use uplink signals for the detection of gravity waves. Changes in amplifier operating parameters are strongly reflected in changes in electrical path length in microwave tubes and consequently in output phase changes. A much greater understanding of the physical processes causing phase changes is necessary if phase stability requirements for detecting gravity waves are to be met.

As a result of such interest, an experimental study program on a VA-876 X-band five-cavity CW klystron amplifier was carried out at Goldstone (Ref. 1). Operating parameter changes were initiated and output phase difference measurements obtained. Included in the program were the pushing factor, heater current changes, drive level variation near saturation, changes in magnet current, and variation in inlet coolant temperature. Theoretical modeling for certain of the aforementioned factors was also initiated so that a comparison between calculation and measurement could be made.

A "gridded-gap" approach was employed to calculate the total drift length including both the gaps and the drift spaces where most of the bunching takes place. Higher-order terms were considered and a second-order time averaged correction was included. Actual physical gap geometry is taken into account in this higher-order term through the beam coupling factor, μ. For the sake of simplicity, one may consider at first the formalism for a two-cavity tube, but subsequent summation yields results for multicavity amplifiers and hence results for more than two cavities will be presented.

II. Theoretical Analysis

Starting with conservation of energy and taking the limit of a small ratio of acceleration caused by RF modulation in the klystron gaps to the initial electrostatic acceleration (Ref. 2), one obtains the following after-time averaging:

$$\Delta\phi = \sum_{i=1}^{\kappa}\left(\frac{\omega l_i}{V_0}\sqrt{1-(V_0/c)^2} + \frac{3}{16}\sum_{j=1}^{i}\frac{\mu_j^2\, V_j^2}{(V_0')^2}\right) \quad (1)$$

where:

ω is the frequency in radians

$\Delta\phi$ is the phase difference between output and input

l_i is the length of the i^{th} driftspace

c is the velocity of light in free space

V_0 is the initial velocity due to electrostatic acceleration

κ is the number of gaps

V_0' is the initial accelerating voltage

V_j is the voltage of the RF field in the j^{th} gap

μ_j is the beam coupling coefficient in the j^{th} gap

The parameter μ_j is given by (Refs. 3 and 4)

$$\mu_j = \frac{2 I_1(\gamma_e b)\left|\int_{-\infty}^{\infty} f_j(z)\exp(i\beta_e z)\,dz\right|}{\gamma_e b\, I_0(\gamma_e a)\, d_j\sqrt{1-\frac{V_0^2}{c^2}}} \quad (2)$$

where:

d_j is the length of the j^{th} gap

b is the electron beam radius

a is the guiding tunnel radius

I_1, I_0 are modified Bessel functions

$$\gamma_e^2 = \beta_e^2 - \beta_0^2 \quad (3)$$

$$\beta_e = \omega/V_0 \quad (4)$$

β_0 is the wavenumber

The electric field envelope function, $f_j(z)$, in the j^{th} gap, is defined as

$$f_j(Z) = \begin{cases} 1 \\ \left(1-\left(\frac{2Z}{d_j}\right)^2\right)^{-1/2} \\ \cosh m_j z \\ 0\text{, outside the gap} \end{cases} \quad (5)$$

where. $f_j(z) = 1$ is chosen if the tunnel mouth ends that open onto the j^{th} gap are blunt or rounded as in the VA-876 klystron;

$$f(Z) = \left(1-\left(\frac{2z}{d_j}\right)^2\right)^{-1/2}$$

is chosen if the ends are knifelike in profile; $f(z) = \cosh m_j z$ is chosen if the tunnel mouth ends conform to neither of the previous two extremes. The field parameter m_j is somewhat arbitrarily picked to best approximate the fields in the j^{th} gap.

To calculate phase changes due to variations in operating parameters, $\Delta\phi$ may be computed under normal circumstances and then again for the parameter change under investigation. Subtraction yields the desired result, i.e.,

$$\langle\Delta\phi\rangle_{\Delta\text{ parameter}} = \langle\Delta\phi\rangle_{\text{change}} - \langle\Delta\phi\rangle_{\text{normal}} \quad (6)$$

Accelerating voltage changes result in a different initial beam velocity. Magnet current drifts cause variation in both beam diameter and effective initial beam velocity (adiabatic invariants are responsible). A difference in the coolant inlet temperature changes the drift lengths and gap geometry dimensions due to thermal expansion and contraction. All of these effects can be reflected as corrections to formulae (1) through (5), and the results for the VA-876 klystron are compared with experimental results (Ref. 1) in Table 1. In the magnet current case, it was assumed that a little more than 99 percent of the beam energy was initially parallel to the axial Brillouin field. The expansion coefficient used was 0.07 percent/°C (Ref. 5).

III. Conclusion

The agreement between theory and experiment is fairly good, especially considering the number of approximations made in obtaining the hybrid gridded-gap-tunnel-geometry model. Further work on the phase lag effects of drive level changes near saturation is in progress and will be reported at a later time.

References

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Table I. Phase factor magnitudes

Parameter	Calculated factor	Measured factor
Accelerating voltage, deg/V	+0.048[a]	+0.04
Magnet current, deg/A	−1.04[b]	−1.0
Inlet coolant temperature, deg/°C	−1.19	−1.3

[a]+ Sign implies a reduction in phase lag
[b]− Sign implies an increase in phase lag